

Middle–Upper Ordovician conodont biostratigraphy of the Eastern Precordillera, San Juan, Argentina

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MIDDLE–UPPER ORDOVICIAN CONODONT BIOSTRATIGRAPHY OF THE EASTERN PRECORDILLERA, SAN JUAN, ARGENTINA

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Abstract. The La Cantera Formation is a siliciclastic unit with restricted distribution that crops out at the eastern edge of the Villicum range (Eastern Precordillera), province of San Juan, Argentina. Its age has previously been recorded based on index graptolites. Several conglomerate, sandstone, and mudstone samples were collected from the lower and middle members of the La Cantera Formation, which provided conodonts and other microfossils such as ostracoderm plates, gastropods, bryozoans, and fragmented brachiopod shells. The retrieved conodont fauna is poorly diverse and just appears as casts in the mudstone bedding planes. It is composed mostly of elements of the genus *Eoplacognathus* that were recovered from sandstone units and elements of the genus *Pygodus* that appear as casts in the mudstone units. In addition, elements of the genera *Baltoniodus*, *Pygodus*, *Periodon*, and *Erismodus* among others, were retrieved from sandstone units. The conodont associations allow proposing, for the first time, a Middle–Upper Ordovician biostratigraphy for the Eastern Precordillera which includes three conodont zones and subzones, in ascending order: *Lenodus suecicus* Zone (*Pygodus anitae* Subzone), *Pygodus serra* Zone (*Eoplacognathus robustus* Subzone), and *Pygodus anserinus* Zone (Upper Subzone). This new biostratigraphic information provides an accurate correlation of this classic unit from the Eastern Precordillera with other units from the Central Precordillera. Also, the recognition of several hiatuses in different time intervals reveals the instability of the basin during the late Darriwilian–early Sandbian.

Key words. Conodonts. Ordovician. Biostratigraphy. Eastern Precordillera. Argentina.

Resumen. BIOESTRATIGRAFÍA DE CONODONTES DEL ORDOVÍCIO MEDIO–SUPERIOR DE LA PRECORDILLERA ORIENTAL, SAN JUAN, ARGENTINA. La Formación La Cantera es una unidad silicoclástica de distribución restringida que aflora en el borde oriental de la sierra de Villicum (Precordillera Oriental) en la provincia de San Juan. Su edad ha sido registrada previamente en base a graptolitos. Se coleccionaron varias muestras de conglomerados, areniscas y pelitas de los miembros inferior y medio de la Formación La Cantera, que proporcionaron conodontes y microfósiles como placas de ostracodermos, gastrópodos, briozoos y braquiópodos. La fauna de conodontes recuperada es poco diversa o simplemente se pueden recuperar como moldes en pelitas. Se compone principalmente de elementos del género *Eoplacognathus* recuperados de areniscas o elementos del género *Pygodus* que aparecen en pelitas verdes. Se suman elementos de los géneros *Baltoniodus*, *Pygodus*, *Periodon* y *Erismodus*, entre otros, que se recuperaron de areniscas y areniscas conglomerádicas. Las asociaciones de conodontes permiten proponer por primera vez la bioestratigrafía de conodontes del Ordovícico Medio–Superior para la Precordillera Oriental, reconociendo tres zonas y subzonas de conodontes, en orden ascendente: Zona de *Lenodus suecicus* (Subzona de *Pygodus anitae*), Zona de *Pygodus serra* (Subzona de *Eoplacognathus robustus*) y Zona de *Pygodus anserinus* (Subzona Superior). Estos nuevos datos bioestratigráficos proporcionan una correlación precisa de esta unidad clásica de la Precordillera Oriental con aquellas unidades de diferentes localidades de la Precordillera Central. Esta correlación permite reconocer varios hiatos en diferentes intervalos de tiempo que revela la inestabilidad de la cuenca durante el Darriwiliano tardío–Sandbiano temprano.

Palabras clave. Conodontes. Ordovícico. Bioestratigrafía. Precordillera Oriental. Argentina.

THE LOWER Paleozoic stratigraphy of the Villicum Range in the Eastern Precordillera (Fig. 1) has been intensively studied since the seventies (Baldís & Blasco, 1975; Furque & Cuerda, 1979). The recognized Ordovician stratigraphic units

in this area, in ascending order, are the La Silla, San Juan, Los Azules, La Cantera, La Pola, and Don Braulio formations (Fig. 1.2). The La Silla and San Juan formations are composed of carbonate rocks, whereas the other units are

siliciclastic. The Rinconada Formation (Devonian) overlies the Lower Paleozoic units through an unconformity (Peralta, 1993) (Fig. 1.2).

The La Cantera Formation was defined by Furque & Cuerda (1979) and amended by Baldi *et al.* (1982). The type section is located in the Don Braulio creek, eastern flank of Villicum Range. Peralta (1993) recognized three members for this unit named as Lower, Middle, and Upper, characterized by conglomerate, sandstone, and mudstone beds, respectively. This author proposed that the La Cantera For-

mation shows erosive contact with the Middle Ordovician Los Azules Formation represented by an abrupt sedimentary change. Heredia *et al.* (2014) indicated that the La Cantera Formation covers paraconformably the Los Azules Formation. This contact is well displayed at the La Pola creek, where a colored hardground represents this sedimentary change between the black fine clastic deposits of the uppermost part of the Los Azules Formation and the pale green mudstone at the basal part of the La Cantera Formation (Fig. 2).

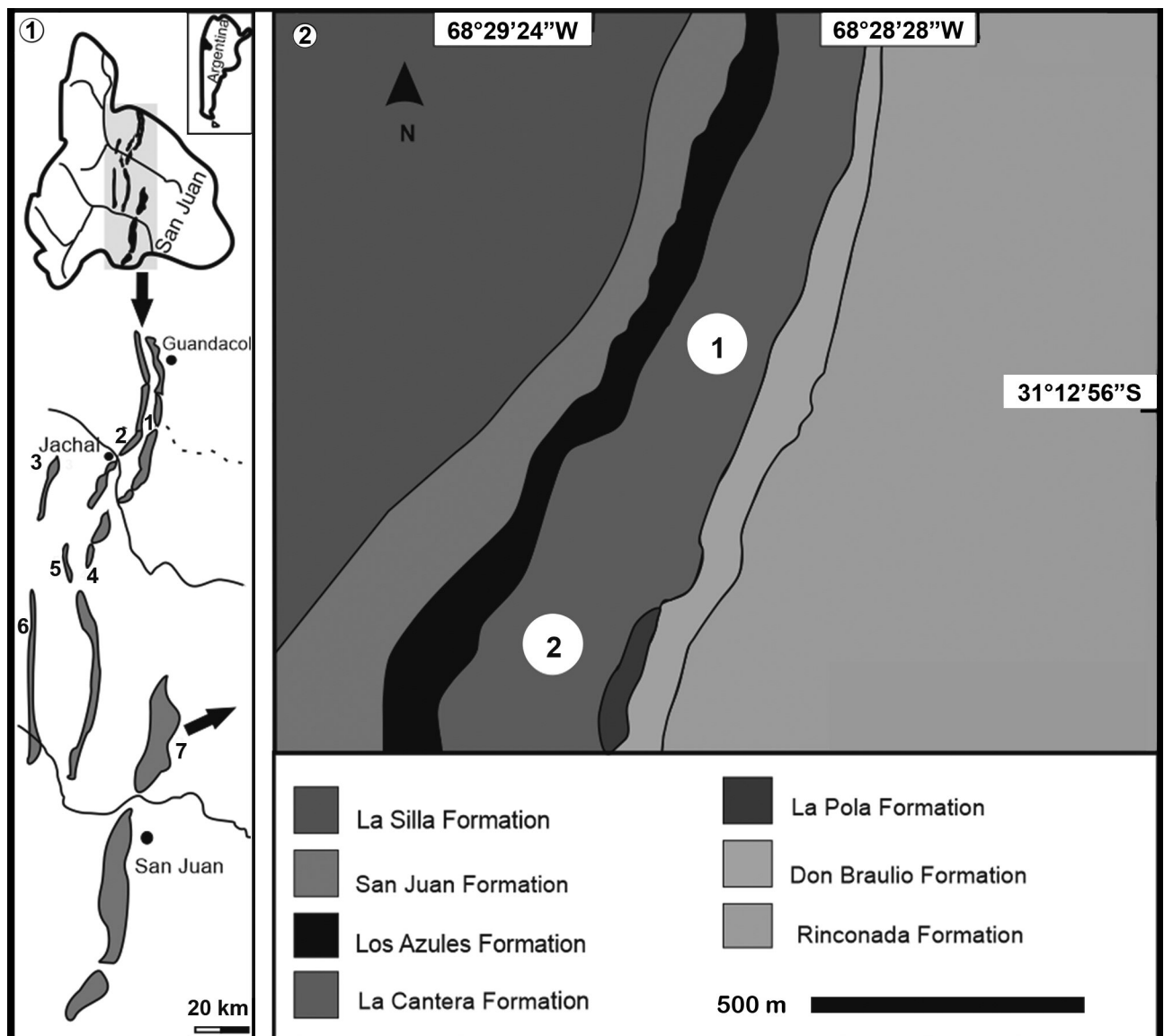


Figure 1. Location maps. 1, Precordilleran localities mentioned in text: 1, Cerro Viejo section; 2, Los Amarillitos section; 3, Las Aguaditas section; 4, Cerro La Chilca section; 5, Las Chacritas section; 6, Sierra La Invernada section; 7, Don Braulio and La Pola sections. 2, Geological map of the eastern edge of the Villicum range, 1: Don Braulio section and 2: La Pola section.

The La Cantera Formation age has previously been determined based on index graptolites. Peralta (1986) studied the graptolite associations from the Middle Member of this unit recording the *Hustedograptus teretiusculus* and the *Nemagraptus gracilis* zones (upper Middle Ordovician–lower Upper Ordovician). Recently, Kaufman (2019) recognized the *Pterograptus elegans* conodont zone in the Lower Member and the *Hustedograptus teretiusculus* and *Nemagraptus gracilis* graptolite zones in the Middle Member in La Pola and Don Braulio creeks.

Albanesi *et al.* (1995) provided the first mention of conodonts and arandaspid plates from the La Cantera Formation. These elements were retrieved from a boulder included in the conglomerate of the Lower Member, recording the *Eoplacognathus lindstroemi* Subzone. Later studies by Heredia *et al.* (2014, 2017a, 2019) led to recognition of the *Lenodus suecicus* Zone (*Pygodus anitae* Subzone) and the *Pygodus serra* Zone (*Eoplacognathus robustus* Subzone) in the Lower and Middle members, respectively.

The purpose of this contribution is to analyze a new and more extensive conodont fauna recovered from the Lower and Middle members of the La Cantera Formation, proposing a new Middle–Upper Ordovician conodont biostratigraphy for the Eastern Precordillera, which allows an accurate correlation with equivalent strata from the Central Precordillera.

Geological setting

The Precordillera is in western Argentina and extends for ~400 km through the provinces of La Rioja, San Juan, and Mendoza. The Paleozoic folded belt rocks of the Precordillera are well exposed along a series of N–S trending thrust belts which include Cambrian to Middle Ordovician carbonate rocks followed by Middle–Upper Ordovician siliciclastic successions, Silurian, and Devonian clastic marine rocks, and Upper Paleozoic glacial, shallow marine and continental deposits. The Precordillera has been subdivided into three morphostructural units, the Eastern (Ortiz & Zambrano, 1981), Central (Baldis & Chebli, 1969), and Western Precordillera (Baldis *et al.*, 1982).

The Middle–Upper Ordovician siliciclastic units from the eastern flank of the Eastern Precordillera cropping out at

the Don Braulio (north and south sections) and La Pola creeks are analyzed and described herein. In these sections, Los Azules Formation is about 40 m thick and composed of black shale and mudstone, with graptolites, trilobites and conodonts as the most conspicuous faunas, which have contributed dating it as lower–middle Darriwilian. The conodont–graptolite association recovered from the basal part belongs to the *Lenodus crassus* and *Lenodus pseudoplanus* conodont zones, and to the *Levisograptus dentatus* graptolite Zone (Mestre, 2013, 2014; Kaufmann, 2019; Mestre & Heredia, 2020). On the other hand, its middle and upper parts are characterized by graptolites from the *Holmograptus lentus* and *H. spinosus* zones (Kaufmann, 2019). The Los Azules Formation is paraconformably covered by the green shale of the La Cantera Formation. This contact is defined by a coarsified surface of ochre color, which extends 5 cm in the overlying beds (Fig. 2).

The La Cantera Formation is characterized by greenish and brownish conglomerate, sandstone, and shale about 138 m thick. To the base, the Lower Member is mainly composed of mudstone interbedding with conglomerate and bioclastic sandstone, whereas to the top it shows thick conglomerate beds 30–38 m thick. The Middle Member is transitional with the Lower Member and consists of sandstone and shale 40 m thick, and the Upper Member represents a thinning fining-upward succession 60 m thick with intense syndepositional deformation to the top (Fig. 2). In the La Pola creek section, the La Cantera Formation is overlain by La Pola Formation (lower Sandbian) (Heredia & Milana, 2010), while in the Don Braulio creek section, this unit is unconformably covered by the Don Braulio Formation (Hirnantian) (Benedetto, 1986; Astini, 2003).

Studied samples from the La Cantera Formation come from both brownish conglomerate–sandstone deposits from Don Braulio creek (southern margin) and green shale beds from La Pola creek (Lower Member), and also from dark brownish sandstones from the Middle Member (Figs. 1–2).

The findings of graptolites and casts of conodonts in the La Cantera Formation have allowed it to be assigned to the Middle–Upper Ordovician with the recognition of the *Pterograptus elegans* graptolite Zone and *L. suecicus* conodont Zone at the Lower Member (Heredia *et al.*, 2017b; Kaufmann, 2019), followed by the *Hustedograptus teretiusculus* and

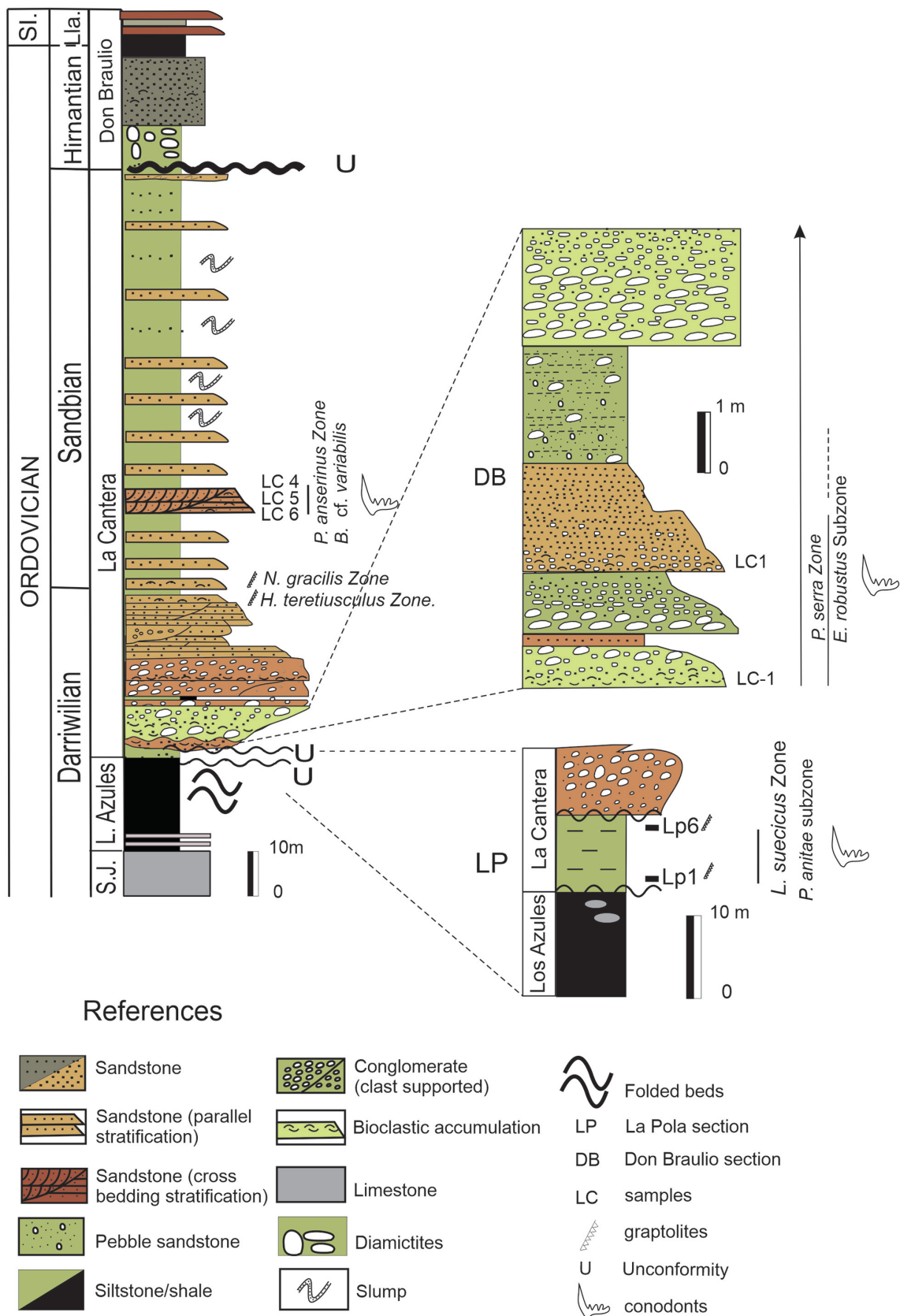


Figure 2. Stratigraphic column with vertical distribution of the key conodonts and graptolites retrieved from the La Cantera Formation.

Nemagraptus gracilis graptolite zones at the Middle Member (Peralta, 1993).

A review of the material originally described by Albanesi *et al.* (1995) allows to interpret that the samples studied by these authors were obtained from two different stratigraphic levels, one from a boulder from the La Cantera Formation (Don Braulio creek section, upper Darriwilian) which provided a few arandaspid plates and conodonts referred to the *P. serra* Zone, probably *E. lindstroemi* Subzone, and the other with conodonts and fish plates from the La Pola Formation (La Pola creek section), which are in line with the conodont fauna described by Heredia & Milana (2010) from the La Pola Formation, allowing to conclude a Sandbian age (*Amorphognathus tvaerensis* Zone) for this arandaspid association. Furthermore, a review of the morphology of the dextral Pa element displayed in Albanesi *et al.* (1995, pl. 2, fig. 2) shows characters more compatible with *Eoplacognathus robustus* Bergström rather than *E. lindstroemi* (Hamar); an aboral Scanning Electron Microscope (SEM) microphotograph of this element could perhaps facilitate a more accurate taxonomic assignment following Heredia & Mestre (2019) criteria.

Heredia *et al.* (2017b, 2019) reported *Pygodus anitae* Bergström from the lowermost beds of the La Cantera Formation in the La Pola creek section, and *Eoplacognathus robustus* from sandstone beds in the base of conglomerates from the Lower Member of the Don Braulio creek section. In addition, Kauffman (2019) illustrated several conodonts from sandstone and mudstone beds from the Lower Member of the La Cantera Formation.

MATERIALS AND METHODS

The conodont samples were collected from two sections of the La Cantera Formation: Don Braulio and La Pola creeks (Figs. 1–2). A total weight of 8 kg represented by 2.5 kg of green shales for six levels (LP samples) and 5.5 kg from fossiliferous sandstones from three levels (LC samples 1, 4, and 6) (Tab. 1). Other samples provided conodont specimens and ostracoderm plates, with a total weight of 8.5 kg from fossiliferous sandstone beds LC-1, 0, 2, 3, 5 (only fertile samples are mentioned in Tab. 1).

Initially, 1–2 kg of each sample were dissolved in dilute formic acid (Stone, 1987) with additional material processed

if needed. Conodonts were retrieved from five fertile samples (Fig. 2), recovering *ca.* 112 identifiable conodont elements (from 315 complete and fragmented elements). The illustrated conodont elements and ostracoderm fish plates are housed in the collection of the INGEO (Instituto de Geología “Emiliano Aparicio”) at the Universidad Nacional de San Juan, under the code INGEO MP.

Conodonts

The retrieved conodonts from the La Cantera Formation were frequently broken but their surfaces and textures were well recognized, so almost all specimens were easily identified at genus and species level. Fourteen species were identified (Figs. 3–5): *Eoplacognathus reclinatus* (Fåhræus, 1966), *E. robustus* Bergström, *E. lindstroemi*, *Panderodus gracilis* Branson and Mehl, *Periodon aculeatus* Hadding, *Protopanderodus varicostatus* Sweet & Bergström, *Pygodus anitae* Bergström, *P. serra* (Hadding, 1913), *Baltoniodus* cf. *B. prevariabilis*, *Baltoniodus* cf. *B. variabilis*, *Erraticodon* cf. *E. balticus*, *Pygodus* cf. *serra*, *Drepanoistodus* sp., and *Erismodus* sp. (Tab. 1).

Some species were selected for description. Since many others are frequently mentioned in the literature, it was unnecessary to include their taxonomic characterization.

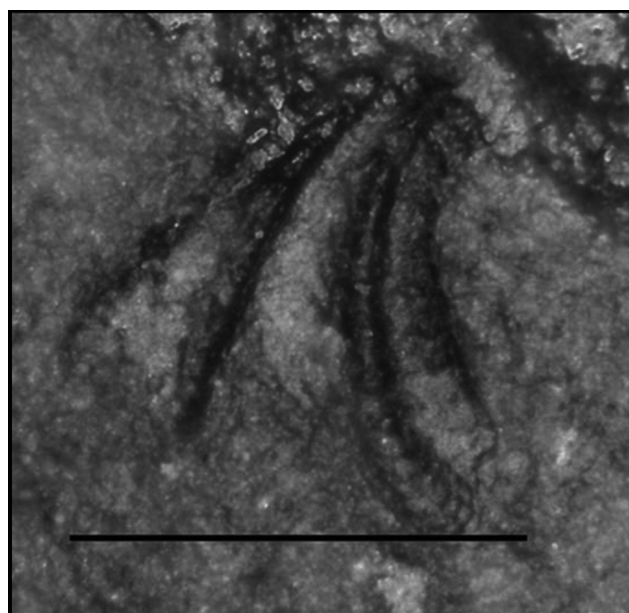


Figure 3. Conodont from the Lp6 sample from the La Cantera Formation, La Pola creek, *Pygodus anitae* Bergström, Pa element, INGEO MP 3800(2). Scale bar= 0.1 mm.

TABLE 1 – Distribution and abundance of conodont species per sample from the study section.

Zone	<i>L. s.</i>	<i>Pygous serra</i>		<i>Pygodus anserinus</i>			
Subzone	<i>P. a.</i>	<i>E. robustos</i>		Upper Subzone			
Genera and species / sample	LP6	LC -1	LC 1	LC 4	LC 5	LC 6	Total
<i>Baltoniodus</i> cf. <i>B. prevariabilis</i>		6	4				10
<i>Baltoniodus</i> cf. <i>B. variabilis</i>				4	1	1	6
<i>Eoplacognathus lindstroemi</i>				1	1	5	7
<i>Eoplacognathus reclinatus</i>		2					2
<i>Eoplacognathus robustus</i>		28	27				55
<i>Erraticodon</i> cf. <i>balticus</i>			1				1
<i>Erismodus</i> sp.		1					1
<i>Erismodus</i> sp.						1	1
<i>Periodon aculeatus</i>			11				11
<i>Protopanderodus varicostatus</i>			4				4
<i>Drepanoistodus suberectus</i>			8				8
<i>Drepanoistodus</i> sp.		2					2
<i>Pygodus anitae</i>	6						6
<i>Pygodus serra</i>		1					1
<i>Pygodus</i> cf. <i>serra</i>		1					1
Total	6	41	55	5	2	7	116

Abbreviations: *L.s.*, *Lenous suecicus*; *P.a.*, *Pygodus anite*.

Four species are briefly described below; they are reported from the Eastern Precordillera for the first time. The synonymy lists are condensed, containing only the original citations of species names incorporated in each multielement taxon. In the descriptions, we used the conventional positions (Pa, Pb, Sa, Sb, Sc, Sd, and M) and orientation terms anterior, posterior, and lateral, noting that they do not relate to the anatomical orientation of the elements (see Purnell *et al.*, 2000). Open nomenclature was used in cases where the material is broken and scarce.

SYSTEMATIC PALEONTOLOGY

Order PRIONIODONTIDA Dzik, 1976
Family BALOGNATHIDAE Hass, 1959

Genus *Eoplacognathus* Hamar, 1966

Type species. *Ambalodus lindstroemi* Hamar, 1964. Holotype: Hammar 1964, p.258, pl. 5, figs. 8, 11. Paleontological Museum, University of Oslo, PMO 69791. Locus typicus: Hamar (1964) describes material from two localities. The localities are Kullerud 3 km ESE of Hønefoss, Norway, and Gomnaes on Tyrifjord 11 km SWW of Kullerud. The stratum typicum is a sedimentary breccia at the base of the nodular Ampyx (4a beta) Limestone.

Eoplacognathus reclinatus (Fåhæus, 1966)

Figure 4.1

1966. *Ambalodus reclinatus* Fåhæus, p. 19–20, pl. IV, figs. 3a–b.
1977. *Eoplacognathus reclinatus* (Fåhæus), Lindström, p. 137–138, pl. 2, figs. 1–3 with complete references through 1974.
1998. *Baltoplacognathus reclinatus* (Fåhæus), Zhang, text. fig. 7A–G.

Remarks. The dextral Pa element is pastiniscaphate with a wide basal cavity that occupies all the aboral side (Fig. 4.1). This element agrees well with Bergström's (1971) oral description. Compared to dextral Pa elements illustrated by Stouge *et al.* (2016) and Hints *et al.* (2012), characters like size and width of the posterior outer lobe (*sensu* Mestre & Heredia, 2020) result different.

Materials. One Pa element: INGEO MP 3807(1).

Stratigraphic and geographic distribution. La Cantera Formation, LC-1 sample. Don Braulio creek section, Villicum range.

Genus *Baltoniodus* Lindström, 1971

Type species. *Prioniodus navis* Lindström, 1955. Locus typicus and Stratum typicum: Ånga Quarry, Stora backor, Västergötland, Sweden, 2200 m NE of Vilske Kleva church, quarry disused in 1953, E wall of quarry, limestone *ca.* 7 m above base of Ordovician.

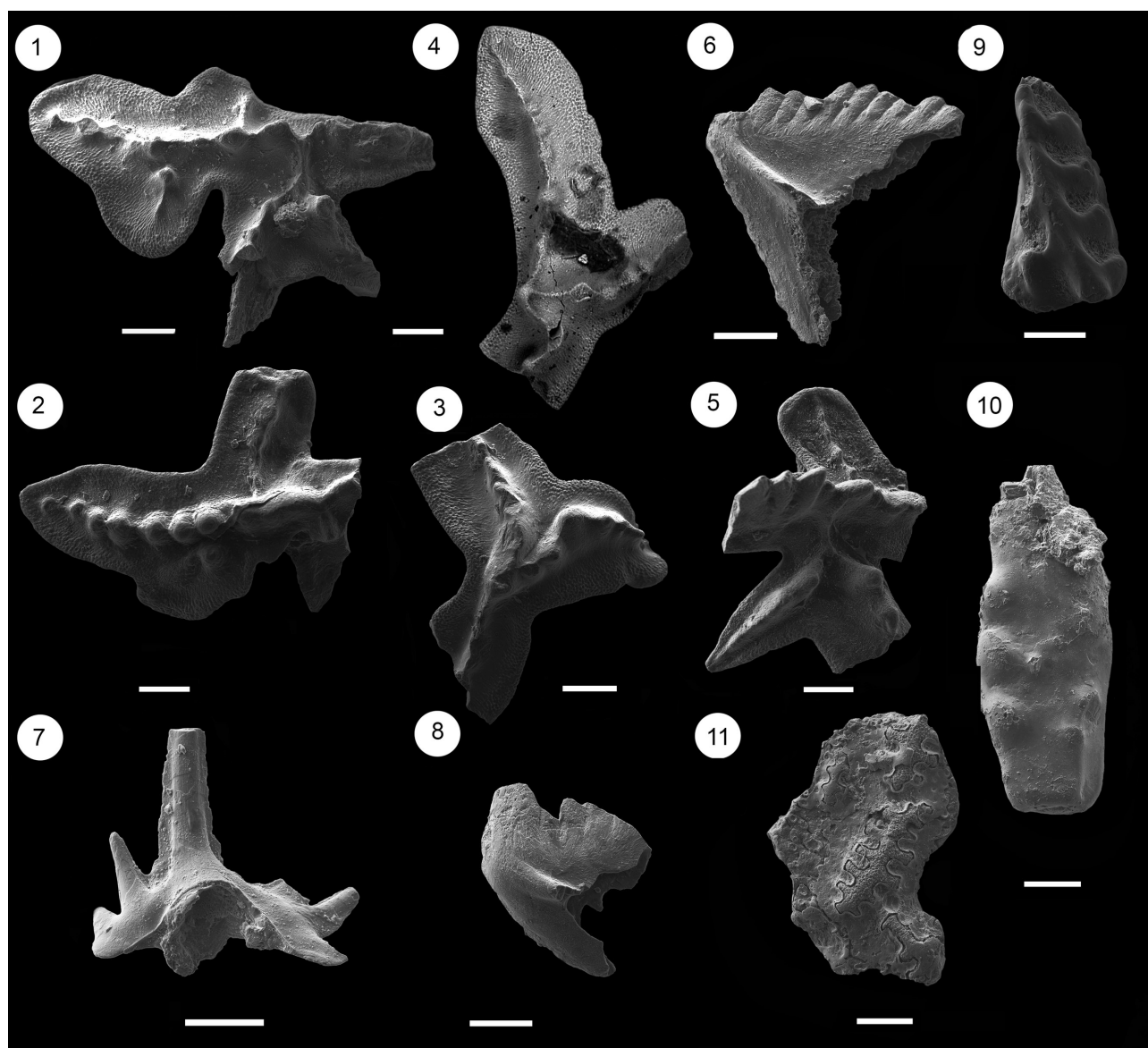


Figure 4. Conodonts and fish plates from the LC-1 sample from the La Cantera Formation. 1, *Eoplacognathus reclinatus* (Fåhæus), dextral Pa element INGEO MP 3807(1); 2–5, *Eoplacognathus robustus* Bergström; 2, dextral Pb element, INGEO MP 3807(2); 3, dextral Pa element, INGEO MP 3802(1); 4, sinistral Pa element, INGEO MP 3802(2); 5, sinistral Pb element, INGEO MP 3802(3); 6, *Pygodus serra* (Hadding), Pb element, INGEO MP 3809(1); 7, *Pygodus* cf. *P. serra*, Pb element, INGEO MP 3809(1); 8, *Erismodus* sp., INGEO MP 3816(1); 9–11, *Sacabambaspis janvieri* Gagnier INGEO MP 3823(1–3). Scale bar = 0.1 mm.

Baltoniodus cf. *B. prevariabilis*

Figures 5.6–5.7

1971. *Prioniodus prevariabilis* Fåhæus, Bergström: pl. 2, fig. 1 (includes synonym list through 1969).

1978. *Prioniodus (Baltoniodus) prevariabilis prevariabilis* Fåhæus, Löfgren: pl. 12, figs. 37–38 (includes synonym list through 1976).

Remarks. P, S, and M elements have been recovered; their conservation is not good enough, and most of them are

broken but some characters remain. P and Sd elements are illustrated.

Pa and Pb elements are mostly broken but their features accord well with the amorphognatiform and ambalodiform elements described by Löfgren (1978).

Materials. Twelve elements: five P elements, five S elements, and two M elements. INGEO MP 3815(1–8), INGEO MP 3801(1–4).

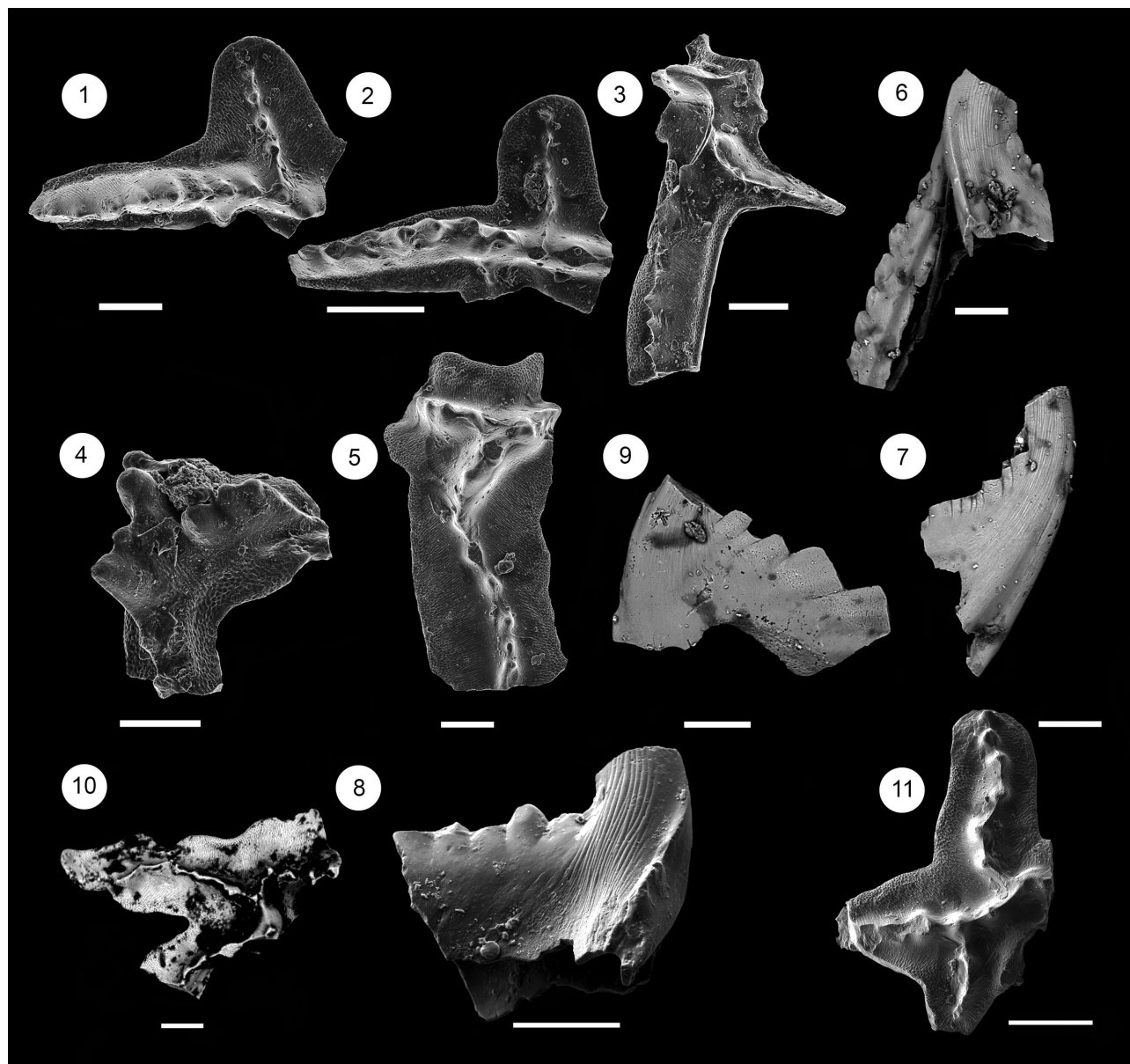


Figure 5. Conodonts from LC-1, LC1, LC4 and LC6 samples from the La Cantera Formation. 1–5, *Eoplacognathus robustus* Bergström, INGEO MP 3600, 1–3, dextral Pa elements, LC1 sample; 4, sinistral Pb element, LC1 sample; 5, dextral Pb element, LC1 sample; 6–7, *Baltoniodus* cf. *B. prevariabilis*, 6, Pa element, LC1 sample, INGEO MP 3801(1); 7, Sd element, LC1 sample, INGEO MP 3801(2); 8, *Baltoniodus* cf. *B. variabilis*, Pa element, LC6 sample, INGEO MP 3812(1); 9, *Periodon* sp., LC1 sample, INGEO MP 3803(1); 10–11, *Eoplacognathus lindstroemi* (Hamar), 10, sinistral Pb element, LC6 sample, INGEO MP 3806(1); 11, dextral Pa element, LC6 sample, INGEO MP 3806(2). Scale= 0.1 mm.

Stratigraphic and geographic distribution. La Cantera Formation, LC-1 and LC 1 samples. Don Braulio creek section, Villicum range.

Baltoniodus cf. *B. variabilis*

Figure 5.8

1962. *Prioniodus variabilis* sp. n., Bergström: p. 51, pl. 2, figs. 1–71.

1971. *Prioniodus variabilis* Bergström, Bergström: pl. 2, fig. 2.

1994. *Baltoniodus variabilis* (Bergström), Dzik: p. 84, pl. 19, fig. 4 (includes synonym list through 1985).

Remarks. P and S elements have been recovered, their conservation is poor, and most of them are broken but some characters remain as shown in Figure 5.8. A fragmented Pa element (adult specimen) accords well with the general description by Bergström (1962) because this species is characterized by having conspicuous ledges along the processes.

Materials. Seven elements: Five P elements and two S elements. INGEO MP 3813(1), INGEO MP 3812(1–6).

Stratigraphic and geographic distribution. La Cantera Formation, LC 5 and LC 6 samples. Don Braulio creek section, Villicum range.

Genus *Pygodus* Lamont et Lindström, 1957

Type species. *Pygodus anserinus* Lamont et Lindström, 1957. Type. Specimen LO 3871 T, figs. 1a–1b. *Stratum typicum* and *Locus typicus*: from grey trilobite-carrying limestone on the small road to Gardslosa Bodar, 1,000 m E of the main road, in the parish of Gardslosa, county Öland, Sweden.

Pygodus serra (Hadding, 1913)

Figure 4.6

1913. *Arabellites serra* n. sp., Hadding: p. 33, fig. 1, 12–13.

1971. *Pygodus serrus* (Hadding), Bergström: p. 149, fig. 2, 22.

1978. *Pygodus serra* (Hadding), Löfgren: p. 98, fig. 32B.

1998. *Pygodus serra* (Hadding), Zhang: pl. 2, fig. 3 (with complete references until 1998).

2001. *Pygodus serra* (Hadding), Rasmussen: fig. 17.1–17.3.

Remarks. Only one Pb (haddingodiform) element was retrieved. Its morphology agrees well with Zhang's (1998) description because this element possesses the typical haddingodiform morphology.

Material. One element: INGEO MP 3810(1).

Stratigraphic and geographic distribution. La Cantera Formation, LC 1 sample, Don Braulio creek, Villicum range.

Biofacies and taphonomic considerations

The specimens of *Pygodus anitae* from the La Pola section (LP 6; Fig. 2) are almost complete and preservation in casts is frequent. On the other hand, the conodonts from conglomerate-sandstone beds from the upper *Pygodus serra* Zone (Fig. 2) are robust in shape, some with broken processes, and no juvenile or delicate forms have been recovered. These observations suggest that the conodont faunas from the La Cantera Formation represent two different environments. The mudstone beds from the *L. suecicus* Zone (*P. anitae* Subzone) were deposited in a relatively shallow low-energy environment. Conversely, the youngest levels with conodonts (*P. serra* Zone) yield conodont genera characteristic of high-energy environments (Armstrong & Owen, 2002) in association with *Sacabambaspis janvieri* Gagnier, an Ordovician ostracoderm that is usually linked to high-energy shallow platform environments (Davies *et al.*, 2007). The LC-1 sample contains dermal plates of *Sacabambaspis janvieri* (Fig. 4.9–4.11) with different degrees of surface preservation, including intense abrasion. Therefore, the accumulation of these levels, represented by the LC-1 and LC 1 samples, occurred in a shallow high-energy environment.

Sacabambaspis janvieri is known from a few localities in South America. It has been described from the Anzaldo Formation in Bolivia (Gagnier *et al.*, 1996), where it is recorded in mixed deposits of a probable Middle Ordovician age due to the co-occurrence with *Erraticodon patu* Cooper, an index conodont for the upper Floian–lower Dapingian interval (Egenhoff *et al.*, 2007; Aceñolaza *et al.*, 2015).

The recovered plates of the sample LC-1 from the La Cantera Formation are older than those described by Albanesi *et al.* (1995). These remains co-occur with specimens of *E. reclinatus* and *E. robustus*, which indicate the lowermost *E. robustus* subzone.

On the other hand, those few ostracoderm plates accompanied by "*E. lindstroemi*" and those abundant materials from the Sandbian La Pola Formation studied by Albanesi *et al.* (1995) are younger. It is important to note that the carbonate-clastic deposits carrying ostracoderm

plates, echinoderm ossicles, and conodonts are frequent in the La Pola Formation (Heredia & Milana, 2010).

The conodont specimens from the samples LC 4, LC 5, and LC 6 (Fig. 2) were retrieved from quartz sandstone beds with fragmented brachiopod shells, broken bryozoans, and echinoderm ossicles, also representing a high-medium energy environment.

Eastern Precordillera Conodont Biostratigraphy

The siliciclastic nature of the La Cantera Formation permits sampling in those levels that have carbonate shells or some carbonate fragments, resulting in a random distribution of the sampled beds along the section. The biozones recorded in this unit lack both first and last occurrences of the index conodont species; however, they are identified based on the record of the index taxa (Fig. 6). ***Lenodus suecicus* Zone, *Pygodus anitae* Subzone.** The record of the *P. anitae* Subzone (upper subzone of the *L. suecicus* Zone) is based on the occurrence of the eponymous species

in the basal part of the Lower Member of the La Cantera Formation (LP 6; Fig. 3). This species occurs in a bedding plane in association with the graptolite *Pterograptus elegans* Holm. The guide species *P. anitae* permits an accurate intercontinental correlation with the Aserian Stage of Sweden (Bergström, 1983), where this species defines the upper subzone of the *L. suecicus* Zone (Zhang, 1998). Equivalent strata were recognized in North China (An & Zheng, 1990; Wang *et al.*, 2018; Jing *et al.*, 2020), Baltoscandia (Bergström, 1971; Viira, 1974; Löfgren, 1978), and North America (Harris *et al.*, 1979).

***Pygodus serra* Zone, *Eoplacognathus robustus* Subzone.** This conodont biozone is recorded in the lowest conglomerate beds of the Lower Member of the La Cantera Formation (Don Braulio creek south). The co-occurrence of *Eoplacognathus robustus*, *E. reclinatus*, and *Pygodus serra* (Fig. 4) in the LC-1 sample allows us to assign these strata to the base of the *Eoplacognathus robustus* Subzone (Fig. 2). This assignment is also supported by the dextral Pb element (Fig. 5.2), which is interpreted as an early form that shows transitionally features with *E. reclinatus* forms. This interpretation is based on the cusp location which is close to the outer margin of the platform, and the angle between the posterior and lateral processes compared with *E. robustus* and *E. reclinatus* forms (Bergström, 1971) (Figs. 7.5–7.7). We note that all the sinistral Pb elements of *Eoplacognathus* are considered as belonging to *E. robustus* (Figs. 7.1–7.4). Beds overlying sample LC 1 yielded only the key species *E. robustus* (Fig. 5.1–5.5).

The *P. serra* biozone correlates with equivalent strata in South China (Wang *et al.*, 2019; Zhang *et al.*, 2019), Baltoscandia (Männik & Viira, 2012; Bergström & Ferretti, 2017), northwestern China (Zhen *et al.*, 2011), and Australasia (Zhen, 2021).

***Pygodus anserinus* Zone, Upper Subzone.** The index species *Eoplacognathus lindstroemi* accompanied by *Baltoniodus* cf. *B. variabilis* were identified in the sandstone beds at the lower–middle part of the Middle Member of the La Cantera Formation in the Don Braulio creek section (Fig. 2), in samples LC 4, LC 5, and LC 6 (Figs. 5.8–5.11). The presence of the Upper Subzone of the *P. anserinus* Zone was confirmed by the identification of *Baltoniodus* cf. *B. variabilis* according to Bergström (1971) and Heredia & Mestre (2017).

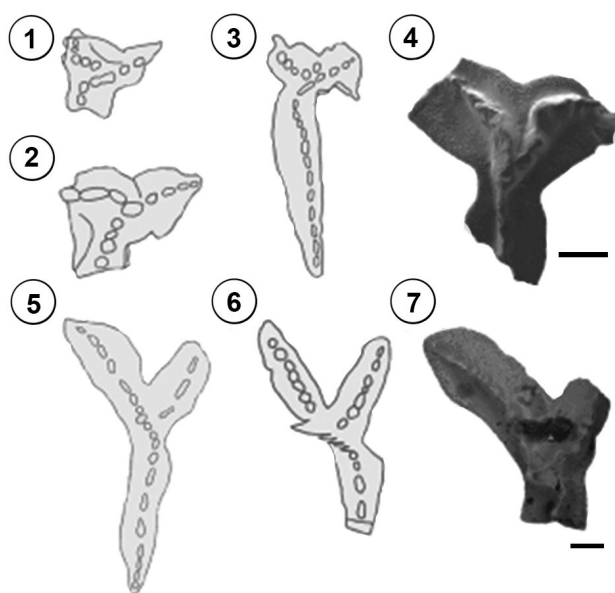


Figure 6. Comparative drawing and SEM photos of *Eoplacognathus* Pb elements. 1–4, *E. robustus* Sinistral Pb elements; 1–2, drawing taken from Heredia (1998, fig. 3c, d); 3, SEM photo of fragmented sinistral Pb element from La Cantera Formation; 4, drawing taken from Bergström (1971, pl.1, fig.14); 5 and 7, *E. robustus*, 6, *E. reclinatus*, Dextral Pb elements; 5, drawing taken from Heredia (1998, fig. 3e); 6, drawing taken from Bergström (1971, pl. 1, fig. 12); 7, SEM photo of fragmented dextral Pb element from La Cantera Formation. Scale= 0.1 mm (4 and 7), the rest without scale.

System	Series	Stages	Baltic conodont Zones & Subzones		South China Conod. Zones & Subzones	Precordillera Conod. biostrat.	Eastern Precordillera Conod. biostratigraphy		
			Zhang(1997,1998) Bagnoli & Stouge(1997)		Zhang(1998)	Heredia et al. (2017)	This study		
Ordovician	Upper	Sand.	<i>Pygodus anserinus</i>		<i>Y. jianyeensis</i> - <i>P. anserinus</i>	<i>Pygodus anserinus</i>	<i>Pygodus anserinus</i>	upper Subzone	
	Middle	Darrivilian	<i>Pygodus serra</i>		<i>Y. protoramosus</i>	<i>Pygodus serra</i>	<i>Pygodus serra</i>	<i>Pygodus serra</i>	
									<i>Y. foliaceus</i>
					<i>Eoplac. suecicus</i>	<i>Pygodus anitae</i>	<i>Eoplacognathus suecicus</i>	<i>E. suecicus</i>	
						<i>Pygodus lunensis</i>			<i>P. lunensis</i>
			<i>Eoplac. pseudop.</i>	<i>M. ozarkodella</i>	<i>Dzikodus tablepointensis</i>	<i>M. ozarkodella</i>	<i>L. pseudoplanus</i>	<i>L. pseudoplanus</i>	
				<i>M. hagetiana</i>		<i>M. hagetiana</i>			
			<i>Yangtz. crassus</i>		<i>Y. crassus</i>	<i>L. crassus</i>			

Figure 7. Middle–Upper Ordovician Conodont biostratigraphic chart for the Eastern Precordillera (this study), Baltic, South China and Precordillera. Abbreviations: **Sand**, Sandbian; **Eoplac.**, *Eoplacognathus*; **Yangtz.**, *Yangtzeplacognathus*; **fo**, *foliaceus*; **re.**, *reclinatus*; **ro.**, *robustus*; **li.**, *lindstroemi*. The lateral bar indicates the conodont biozones involved in this contribution.

The *P. anserinus* biozone correlates with coeval strata in Newfoundland (Bergström *et al.*, 1974), the Marathon Basin (Bergström, 1978), the Great Basin and Rocky Mountains (Harris *et al.*, 1979), Poland (Dzik, 1994), Sweden (Bergström, 1971, 2007), northwestern China (Zhen *et al.*, 2011), Thailand (Agematsu *et al.*, 2007), Kazakhstan (Tolmacheva *et al.*, 2009), and South China (Zhen *et al.*, 2009; Wu *et al.*, 2016), representing a worldwide distributed Ordovician conodont biozone.

Biostratigraphic regional correlation of Middle–Upper Ordovician strata

A complete Middle–Upper Ordovician conodont biostratigraphy of the Eastern Precordillera is presented here for the first time, recognizing three conodont zones and three conodont subzones (Fig. 6). This information allows us to present an upper Darriwilian (Da3–Da4)–Lower Sandbian (Sa1) conodont biostratigraphic chart for the La Cantera Formation, which is developed only in this sector of

the Eastern Precordillera (Figs. 1, 2).

The *Lenodus suecicus* Zone was properly recognized by the index conodont in Las Aguaditas Formation in the Las Aguaditas and Las Chacritas sections (Central Precordillera) (Heredia *et al.*, 2011, 2017a; Heredia & Mestre, 2013) (Fig. 1.1). The first section provided specimens interpreted as early representatives of this species, whereas the Las Chacritas section contains specimens that show an advanced evolutionary trend (Heredia, 2012; Mestre & Heredia, 2020). Reports of this zone and subzones are also known from the Los Azules Formation (Albanesi & Ortega, 2002, 2016; Ortega *et al.*, 2007). A correlation scheme was developed to show the distribution of the *L. suecicus* Zone in the Precordillera considering evolutionary patterns of this species (Fig. 8.1). The correlation between *Pygodus lunnensis* early form and *P. anitae* early and late forms with early and late forms of *L. suecicus* respectively, is corroborated herein by the co-occurrences of these index species. We propose an accurate correlation between the studied sections

during the *L. suecicus* Zone documenting the record of unconformities for the first time in the Precordillera. Based on this information, we recognize at least two short

hiatuses into the *L. suecicus* Zone that could represent the change of the sedimentary regime from carbonate to clastic in the Darriwilian of the Eastern Precordillera (Fig. 8.1).

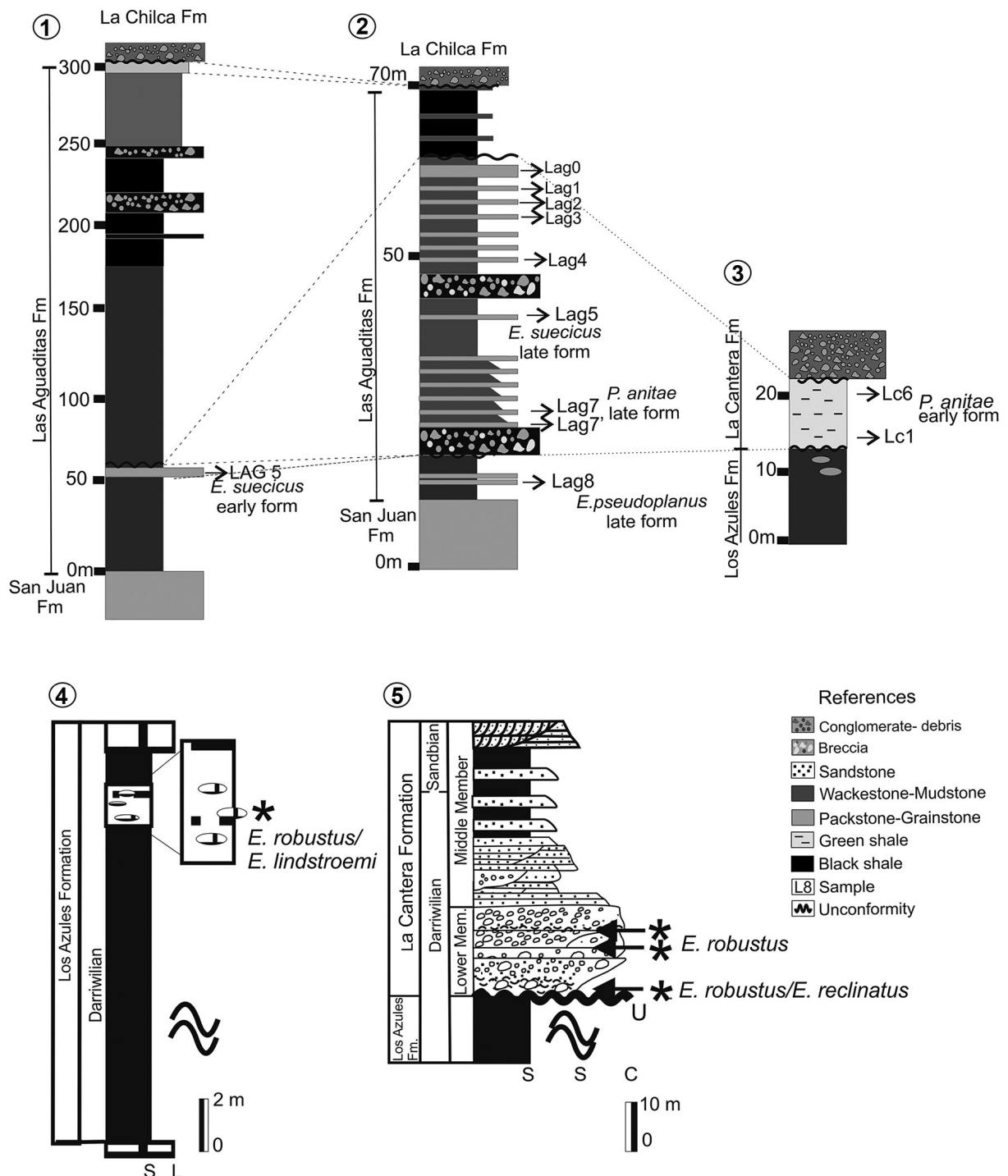


Figure 8. Stratigraphic correlation schemes for the *L. suecicus* Zone and the *Pygodus serra* Zone, *E. robustus* and *E. lindstroemi* subzones between the Eastern and Central Precordillera. 1-3, *L. suecicus* Zone: 1, Las Aguaditas section; 2, Río Las Chacritas section; 3, La Pola section. 4-5, *Pygodus serra* Zone, *E. robustus* and *E. lindstroemi* subzones: 4, Los Amarillitos section; 5, Don Braulio section.

The *Eoplacognathus robustus* Subzone represents the lower and middle parts of the *Pygodus serra* Zone (Bergström, 1971). The oldest record of *E. robustus* in the basin is indicated by the co-occurrence with *E. reclinatus* (LC-1 sample), followed by the occurrence of *E. robustus* (LC 1 sample) in the La Cantera Formation.

The following subzone is represented by the *Eoplacognathus lindstroemi* Subzone (*Pygodus serra* Zone). Early representatives of *E. lindstroemi* along with *E. robustus* from Los Amarillitos section (Figs. 1.1, 2) indicate the basal record of the *E. lindstroemi* Subzone in these deposits (Heredia et al., 2019). The correlation scheme developed for this biozone in the Precordillera considers the evolutionary patterns of this species and presence or absence of its descendants (Fig. 8.2). Both subzones were correlated outside the Precordillera with the Ponón Trehué Formation in the San Rafael Block (Heredia et al., 2019).

The interval that includes the upper *P. serra* Zone to the

lower *P. anserinus* Zone representing the latest Darriwilian contains scarce fossils, except a sandstone bed that has provided many specimens of *Hustedograptus teretiusculus* (Fig. 2).

The Sandbian stage is represented by the *Nemagraptus gracilis* Zone based on the record of the index graptolite (Fig. 9). The base of this graptolite biozone is coeval with the upper part of the *P. anserinus* Zone. This time interval shows a wide distribution in the Precordillera.

The Don Braulio section is the only locality in the Precordillera where the Darriwilian–Sandbian boundary is recorded. The co-occurrence of *Baltoniodus* cf. *B. variabilis* and *Eoplacognathus lindstroemi* corroborates the upper part of the *P. anserinus* Zone (Figs. 2, 6)

The *N. gracilis* Zone in the Central Precordillera is best represented in the Las Aguaditas Formation in Las Aguaditas creek (Fig. 1.1), where the conodonts *P. anserinus*, *Baltoniodus variabilis*, and *E. lindstroemi* indicate the Sandbian

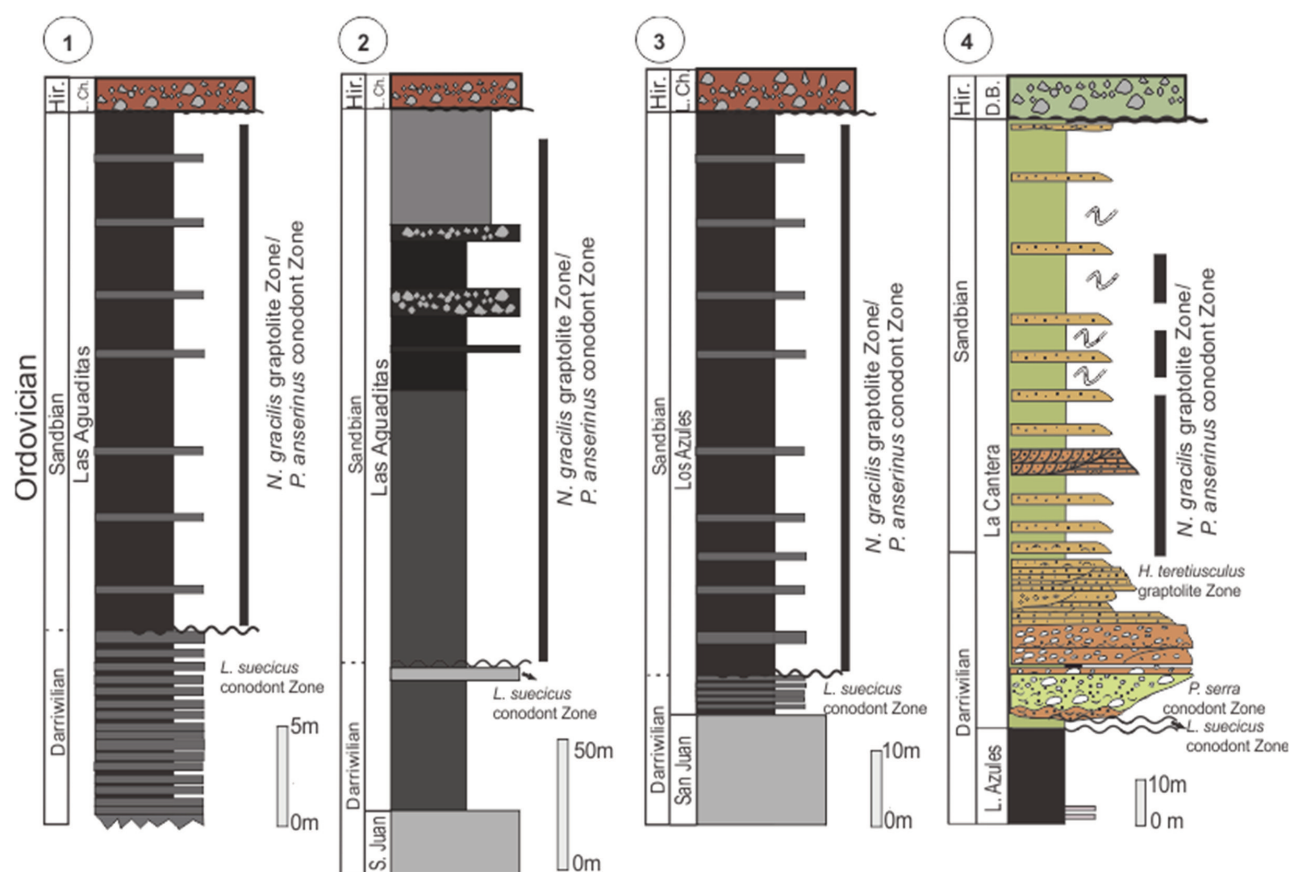


Figure 9. Stratigraphic correlation schemes for the *Pygodus anserinus* Zone between the Eastern and Central Precordillera. 1, Cerro La Chilca section; 2, Las Aguaditas section; 3, Los Gatos section; 4, Don Braulio section.

stage correlating with *N. gracilis*. These outcrops are also recorded in the Las Chacritas and La Chilca sections (Fig. 1.1) overlying black carbonate mudstone beds from the *L. suecicus* Zone (Fig. 9) (Feltes *et al.*, 2019).

Therefore, a possible interpretation of the sedimentary record of Darriwilian–Sandbian deposits can be proposed. The upper part of the *L. suecicus* Zone represents transgressive deposits followed by a change in the sedimentation due to an up-lift inland that is indicated by a coarse input during the *E. robustus* subzone displaying an erosive interval comprised by the *E. foliaceus* and *E. reclinatus* subzones (Fig. 6) (Heredia *et al.*, 2019). The coarse facies are followed by progressive finer facies reaching the major expression in the basin during the *P. anserinus* Zone.

CONCLUSIONS

The worldwide Darriwilian–Sandbian conodont biostratigraphy is mainly based on the evolution of the genera *Lenodus*, *Eoplacognathus*, *Pygodus*, *Baltoniodus*, and *Amorphognathus*, among others. Some of these genera are well represented in the conodont biostratigraphy of the La Cantera Formation. A conodont biostratigraphic chart for the Eastern Precordillera is proposed in the present contribution.

Also, this conodont succession is compared with correlates from the Central Precordillera, being this sedimentary arrangement representative of tectono-sedimentary and sea-level interpretation. Two short hiatuses are recognized into the *L. suecicus* Zone. An important hiatus comprising the *E. foliaceus* and *E. reclinatus* Subzones is identified in the Precordillera. The middle and upper parts (upper *P. anserinus* Zone) of these outcrops and those from the Central Precordillera represent a muddy continental infilling of the Precordilleran basin. Finally, a significant regional biostratigraphic gap is recognized which involves the lower *P. anserinus* Zone and is only represented in the Eastern Precordillera. On the other hand, part of the *L. suecicus* Zone and almost all the *P. serra* Zone are omitted in the Central Precordillera.

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